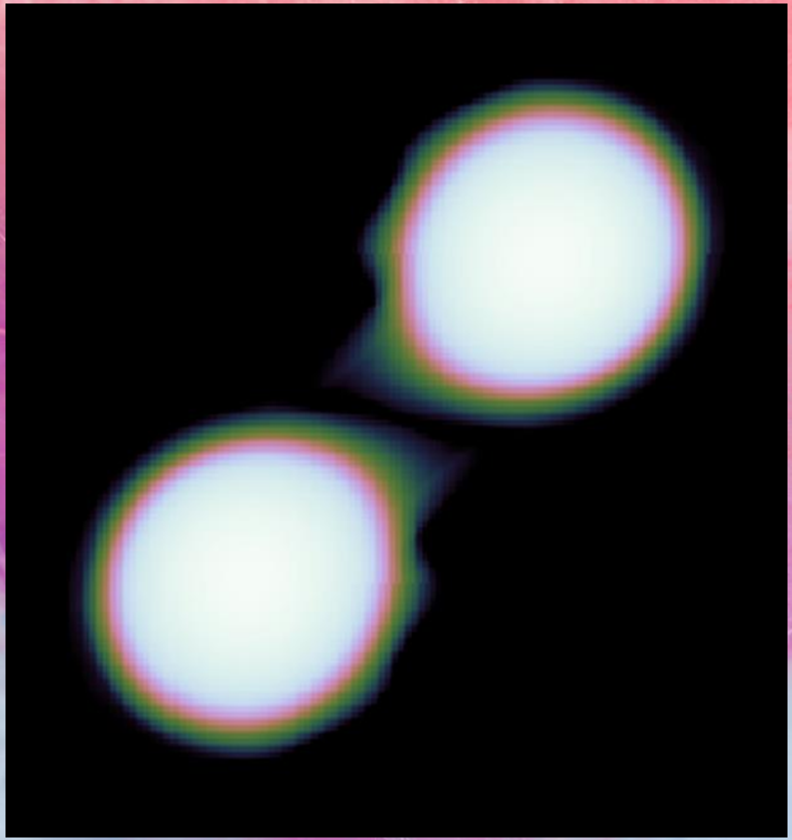
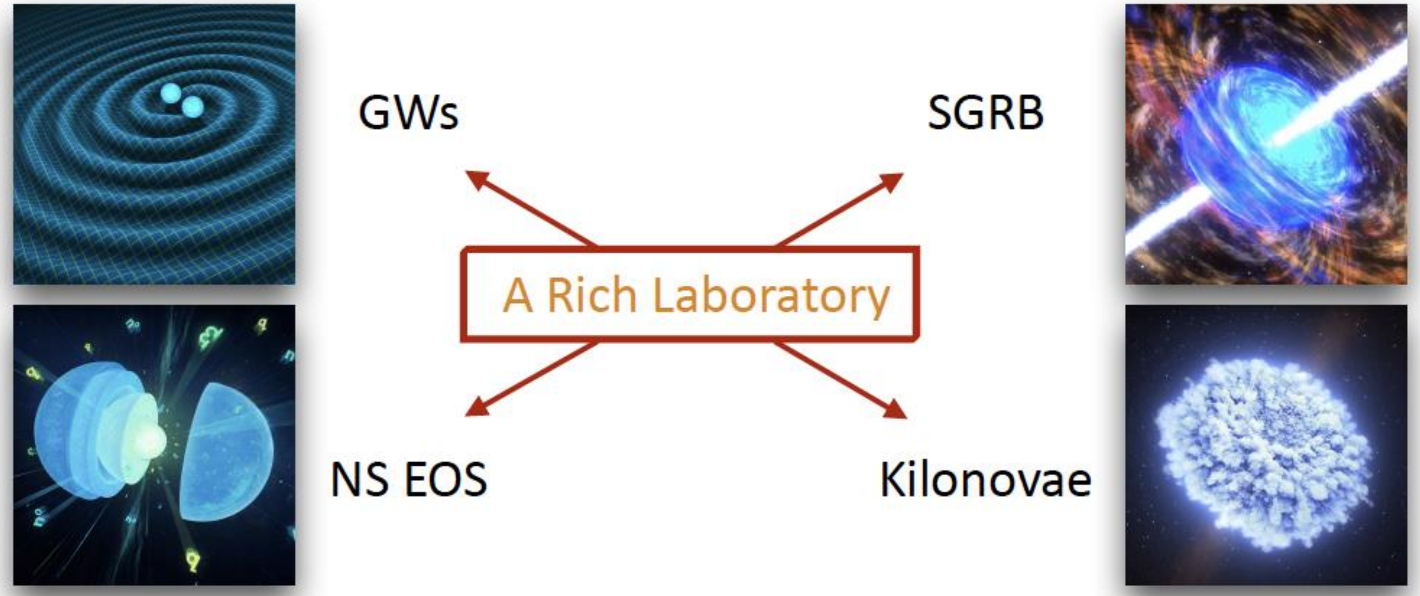
Binary Neutron Star Simulations with Tabulated Equation of State in *Spritz*



Fatemeh Hossein Nouri
Collaboration with Bruno Giacomazzo, Riccardo Ciolfi, Albino Perego & Jay Kalinani
INFN at Milano-Bicocca University

SISSA, November 2025

Why BNS mergers are interesting?

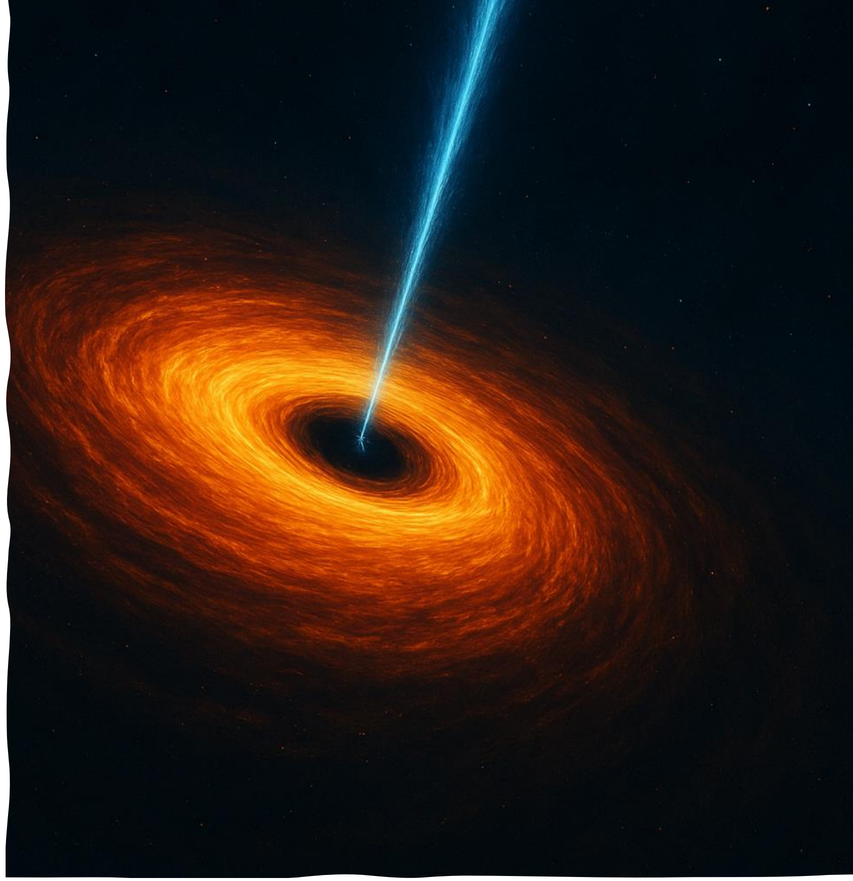


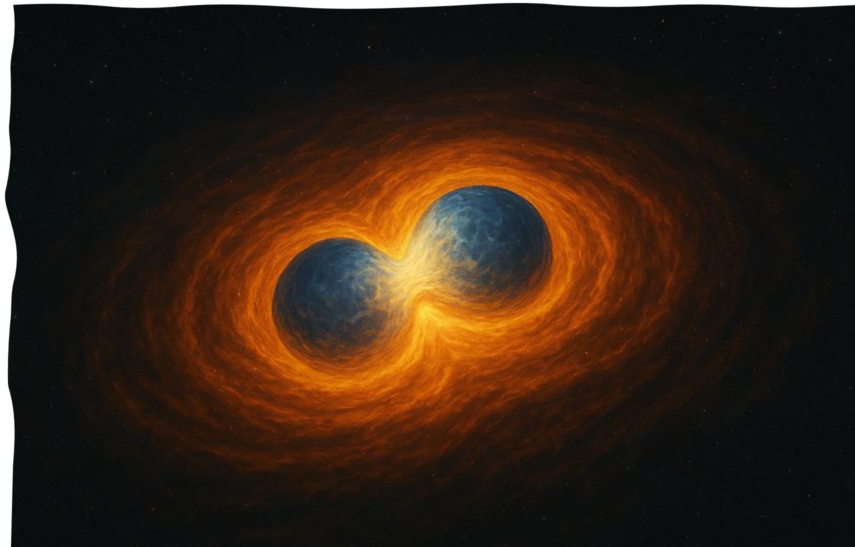
GW170817 : Beginning of a multimessenger astrophysics era with GW sources.

Motivation:

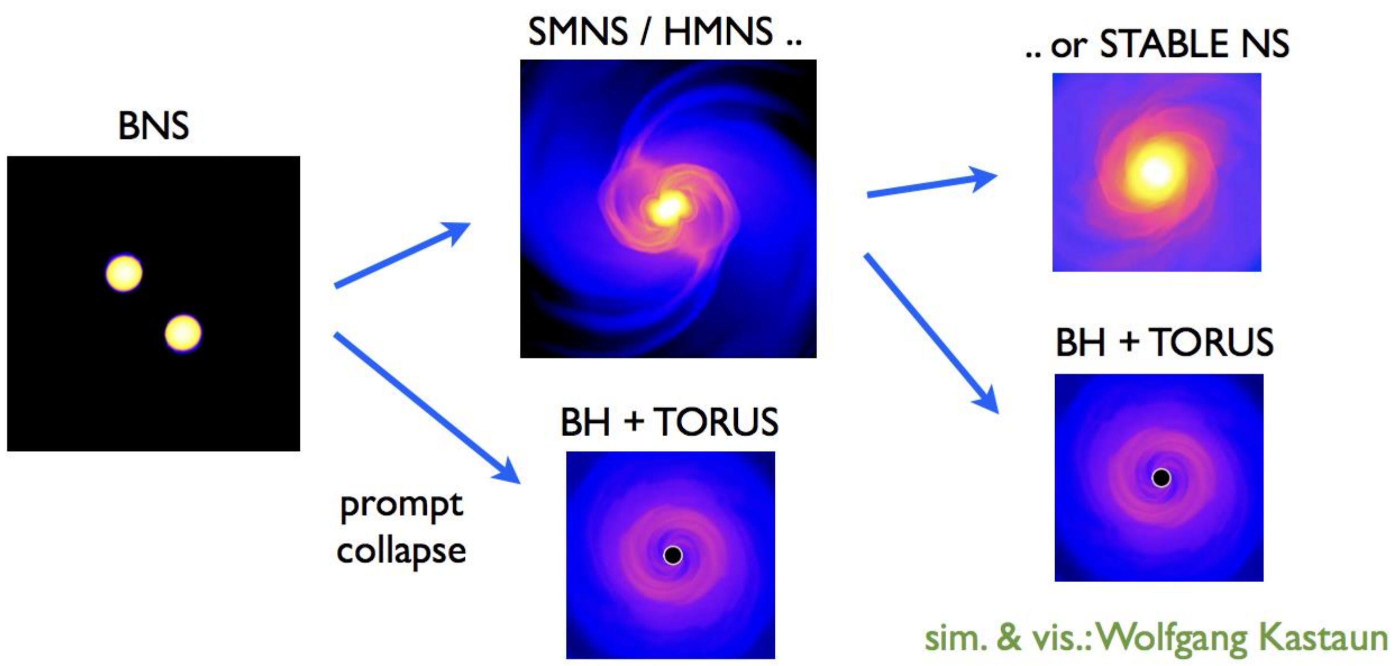
- **GW170817: GW + kilonova + short GRB**
- **The important elements:**
- Tabulated EOS:
  - Includes finite-T, composition, microphysics
  - Needed for shocks, neutrino cooling, thermal remnant structure
- Magnetic fields:
  - Amplified by Kelvin–Helmholtz & MRI
  - Drive angular momentum transport, launch disk winds, power jets
- **Goal:** link microphysics (EOS + B-fields) → GW signals + ejecta + EM counterparts

Image credit: ChatGPT





Possible scenarios for GW170817



Depending on the mass ratio and EOS, we can have different possible scenarios.

Which one is more likely to power relativistic jet and launch massive neutron-rich outflows?

Literature Overview

- **Early GRMHD frameworks (2005–2012)**
  - Duez et al. (2005), Shibata et al. (2005), Giacomazzo & Rezzolla (2006): first GRMHD codes for BNS mergers
- **Magnetic Field Amplification**
  - Kiuchi et al. (2014, 2015, 2018): KH instability & MRI amplify fields → 10^{15}–10^{16} G
- **EOS & Neutrinos**
  - Sekiguchi et al. (2015, 2016): tabulated EOS + weak interactions + neutrino cooling
  - Palenzuela et al. (2015): EOS + neutrino leakage in GRMHD framework
  - Radice et al. (2016–2020): ejecta composition, neutrino winds, r-process
- **Jets & Outflows**
  - Ruiz et al. (2016, 2018): BH-disk systems → jet launching with strong fields
  - Kawamura et al. (2016): role of magnetic field orientation, EOS, neutrinos in jet collimation
  - Ciolfi et al. (2017,2019, 2020): EOS + GRMHD → MHD-driven ejecta, jet formation conditions
- **Long-term: Ejecta & r-process**
  - Nedora et al. (2021): spiral-wave winds, r-process yields; mass ratio and EOS effects
- **Recent Review on GRMHD BNS**
  - Kiuchi (2024): review of 40+ GRMHD BNS studies; highlights EOS + MHD + neutrino interplay

Spritz Code

- Adopts high resolution shock capturing methods to solve GRMHD equations using **HLLE Riemann solver and 5th order reconstruction method**.
- Built on the **Einstein Toolkit** infrastructure
- Physics implemented: **Microphysics and magnetic field**
- Neutrino transport: **Leakage approximation**
- Magnetic field: vector potential evolution using **generalized Lorenz gauge**
- Publicly available on Zenodo: https://zenodo.org/record/4350072
- For implementation of numerical methods, check out papers: *Cipolletta et al. 2020, CQG 37, 135010, Cipolletta et al. 2021, CQG 38, 085021, Kalinani et al. 2022, PRD 105, 103031*
- Tabulated EOS and neutrino leakage successfully tested for stationary single NS.

Challenges:

The status of the code when I joined:

- Stationary NS with tabulated EOS ✓
- Boosted NS with tabulated EOS ✗
- BNS inspiral: The orbital evolution was much faster than expected!!!! ✗

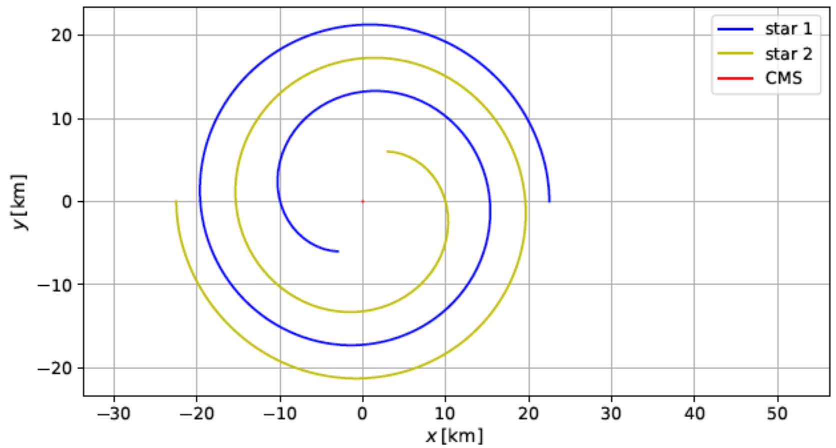
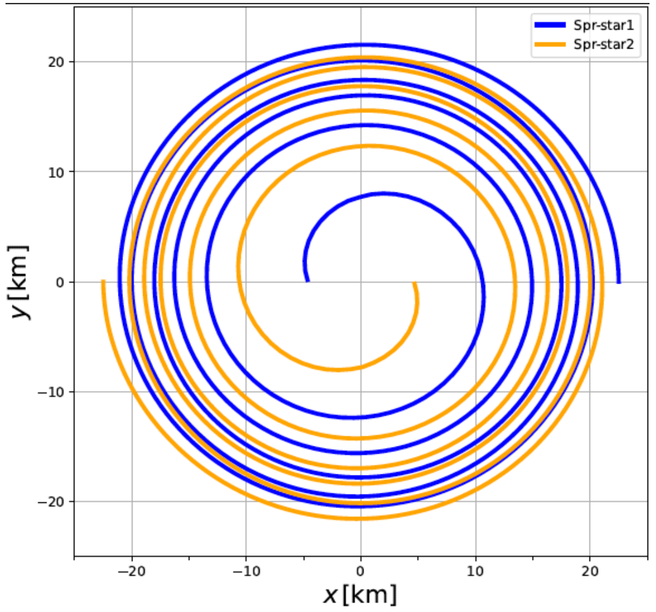
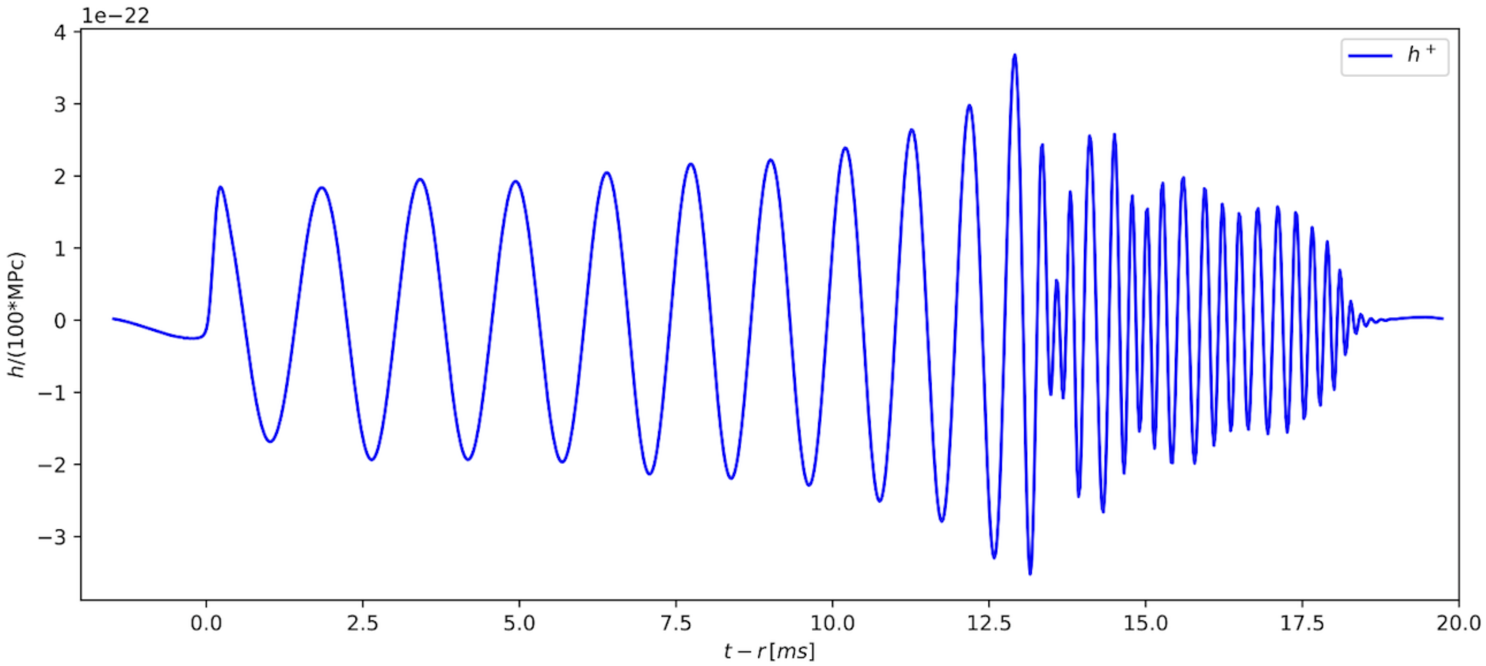


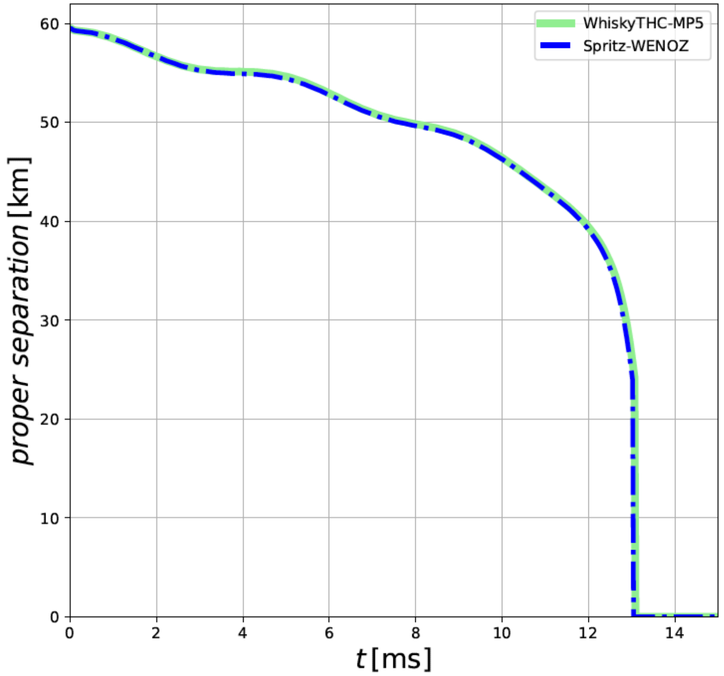
Image credit: Paolo Garimberti's MSc dissertation

Code Validation Tests (Spritz vs WhiskyTHC)

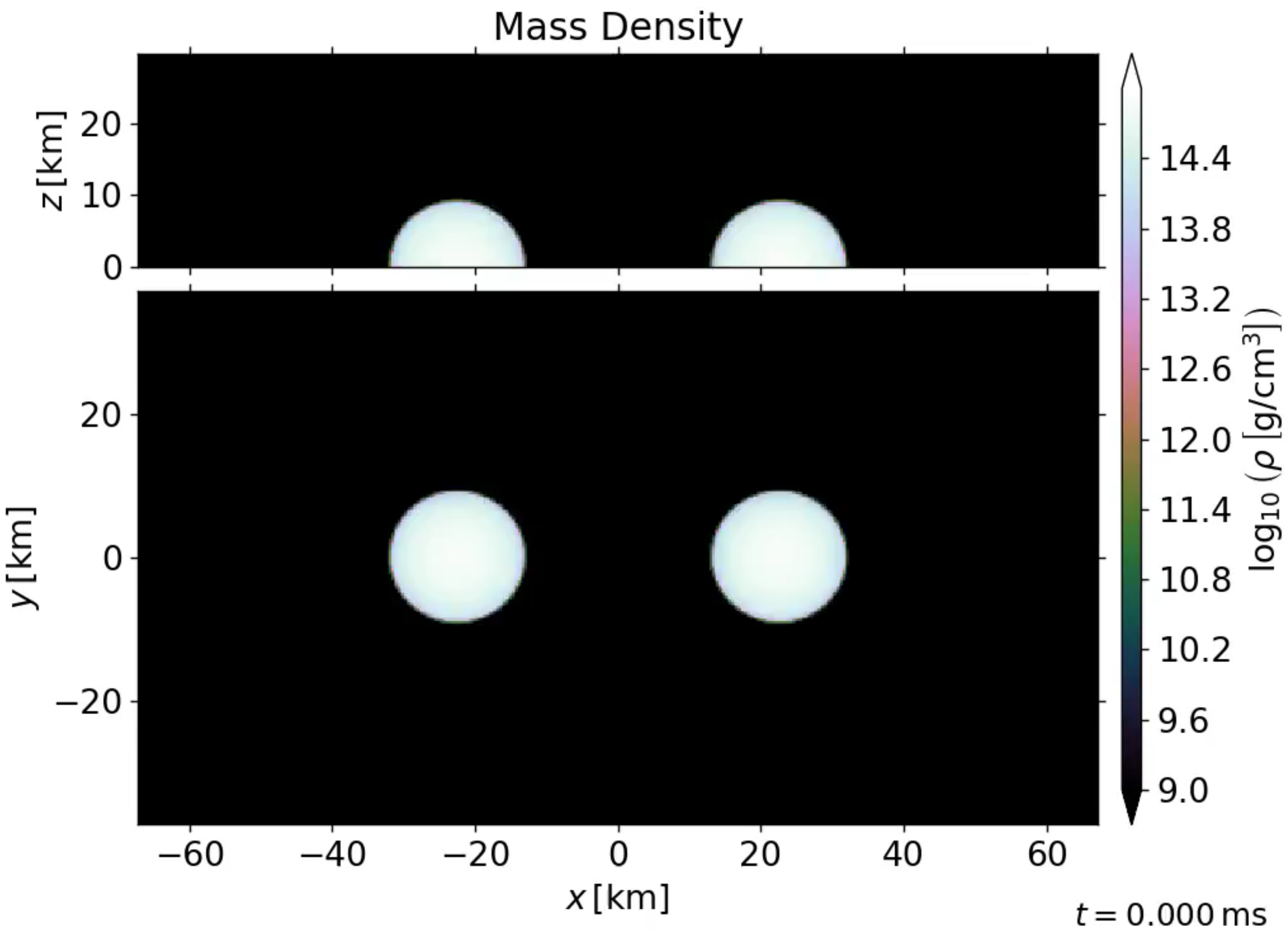
- Equal mass BNS: M_{ADM}= 1.46 $M_{\odot}$
- Initial coordinate separation between the centers: 45 km
- Bombaci-Logoteta (BLhot) EOS
- Initial data: Slice constant temperature T=0.01 MeV
- Resolution for finest grid dx = 0.20 $M_{\odot}$
- Orbital evolution is compared with WhiskyTHC code



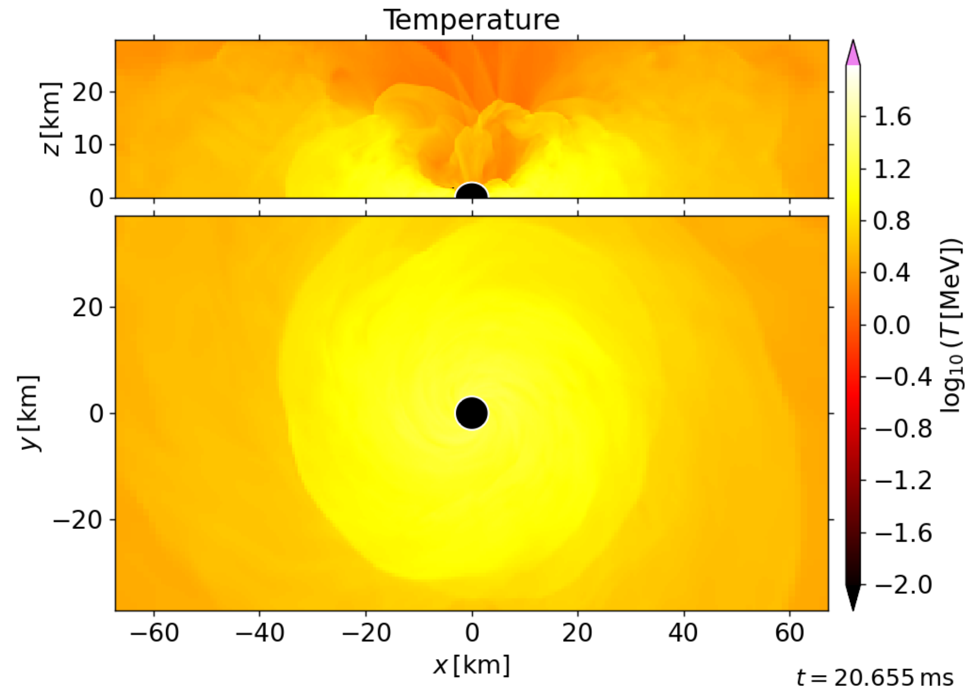


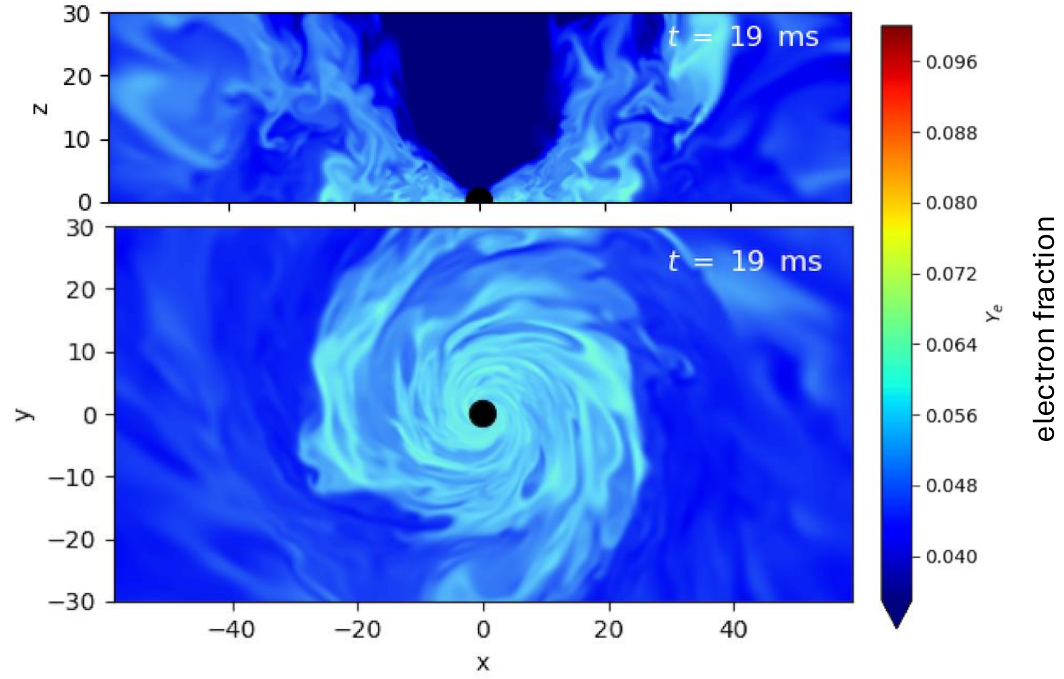


Code Validation Test (hydro)

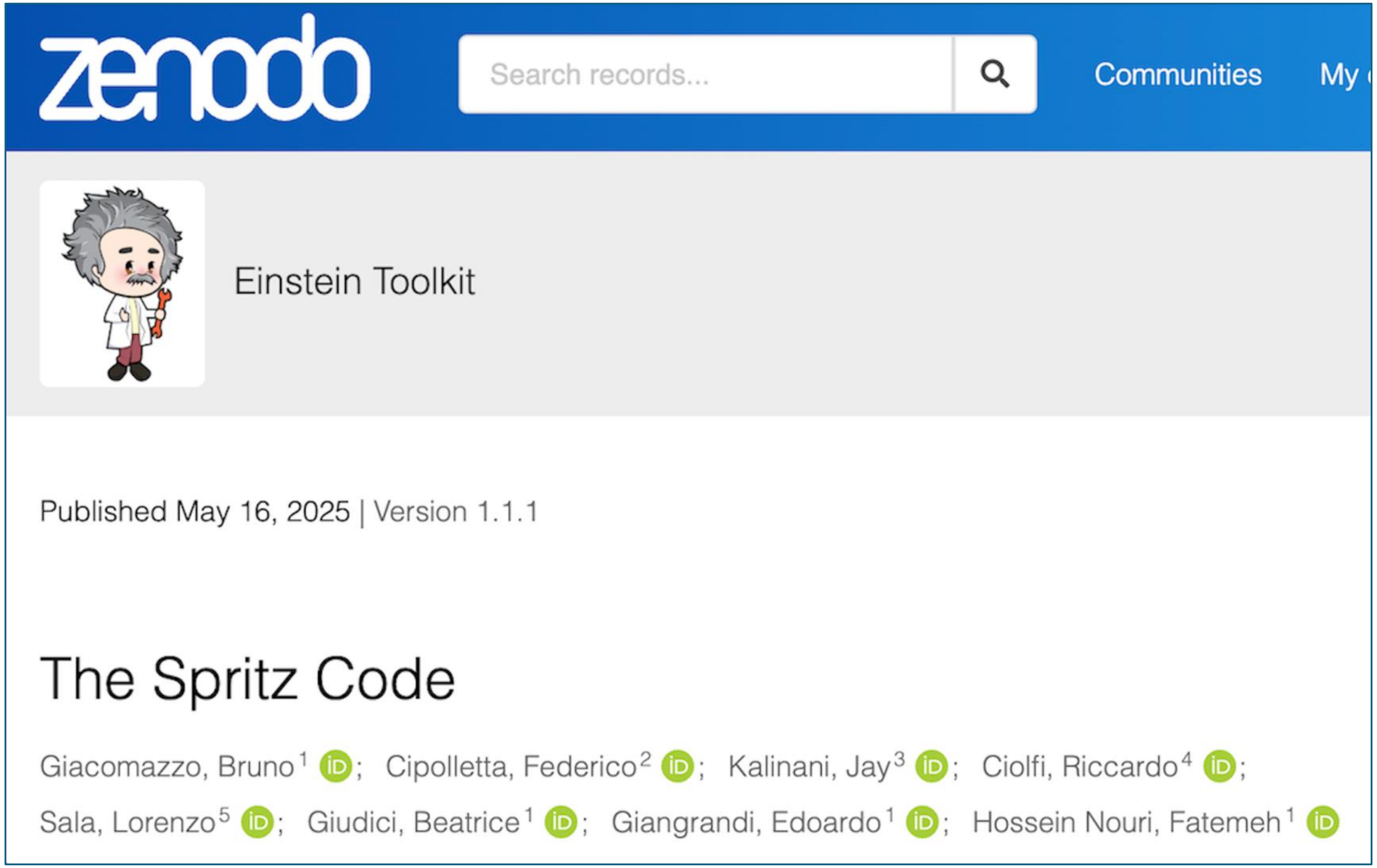


Apparent horizon is formed ~5 ms after the merger, HMNS collapse to BH



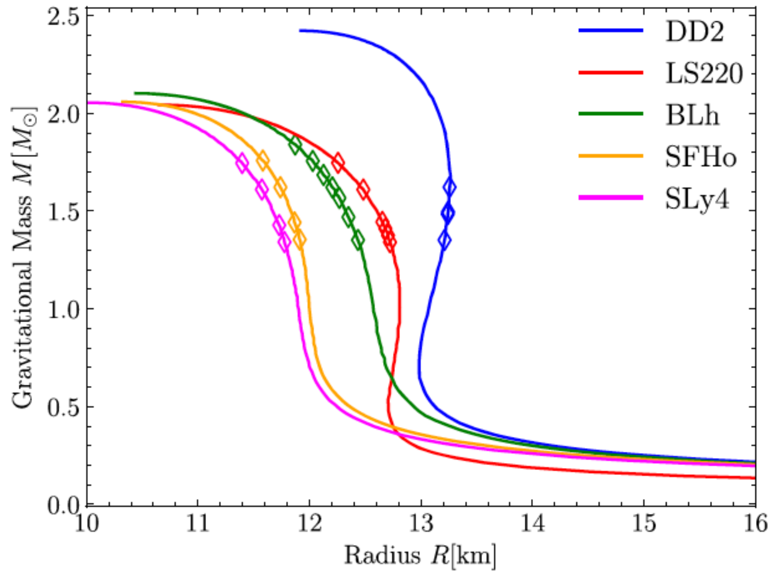


New version of the code is available on Zenodo with recent fixes for microphysical equation of state



Current simulations and the choice of EOS

- Main simulations: Three sets of BNS (two magnetized, one non-magnetized)
- Initial data generated by *FUKA* for two EOS:
- **BLhot**: More modern, microphysical, derived from chiral effective field theory (EFT) and nuclear interactions ➔ long-lived HMNS remnant (> 100 ms)
- **LS220:** Old Skyrme-type liquid-drop model ➔ short-lived HMNS (collapse ~15-30 ms)



Nedora et al. (2021)

Model	EOS	M_{bmax}	B_{max} G	dx	M_1	M_2
LS220_B16_dx015	LS220	1.50229	10^{16}	0.15	1.3624	1.3624
LS220_B0_dx015	LS220	1.50229	0	0.15	1.3624	1.3624
BLhot_B16_dx015	BLhot	1.49047	10^{16}	0.15	1.3624	1.3624

Initial Setup

- Equal- mass binary system 1.3624 $M_\odot$ (chirp mass of GW170817)
- Binary separation 45 km
- Resolution for finest grid dx = 0.15 $M_\odot$
- Initial magnetic field: Poloidal configuration $B = 10^{16}$ G

Why such a large magnetic field?

- to compensate for insufficient resolution
- to study highly magnetized post-merger system
- to enhance magnetic field effects
- more favorable condition for possible jet formation

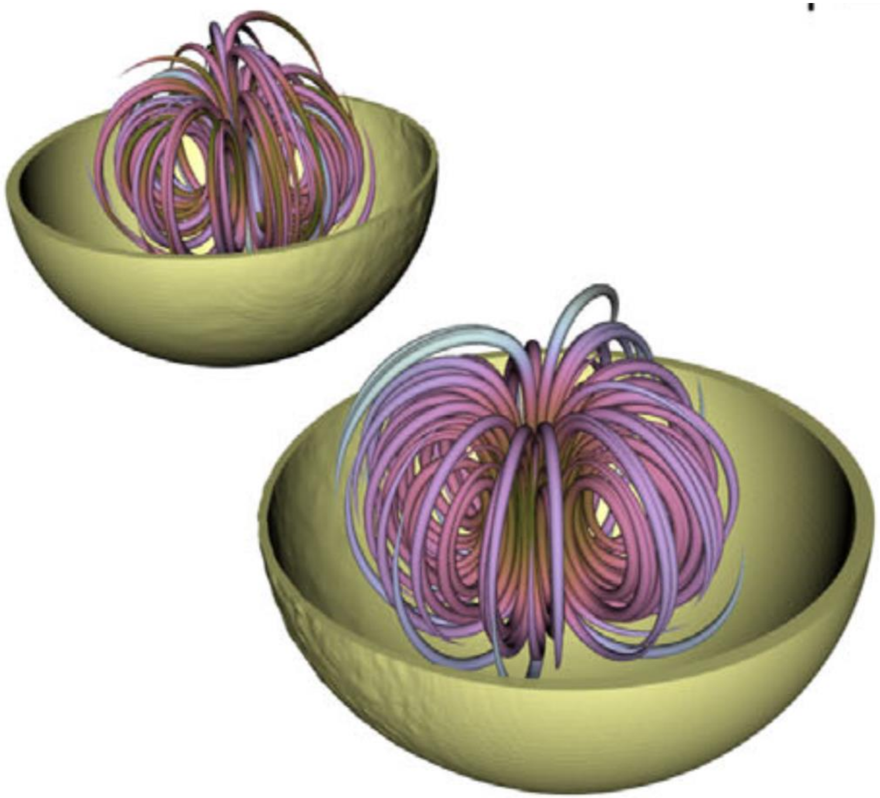
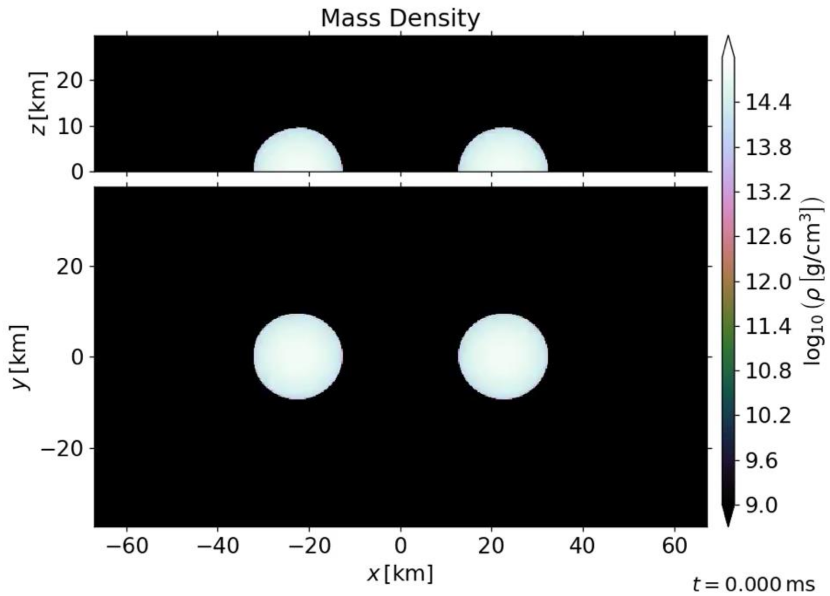
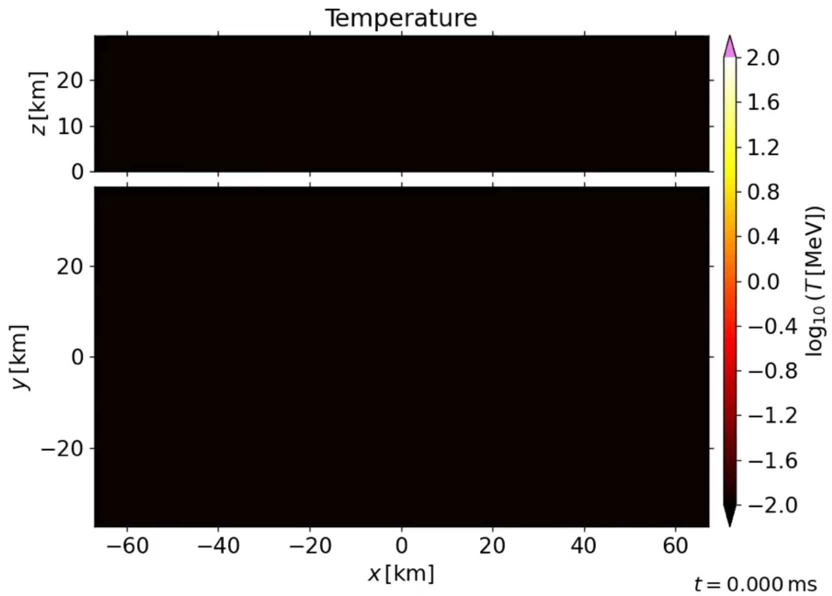
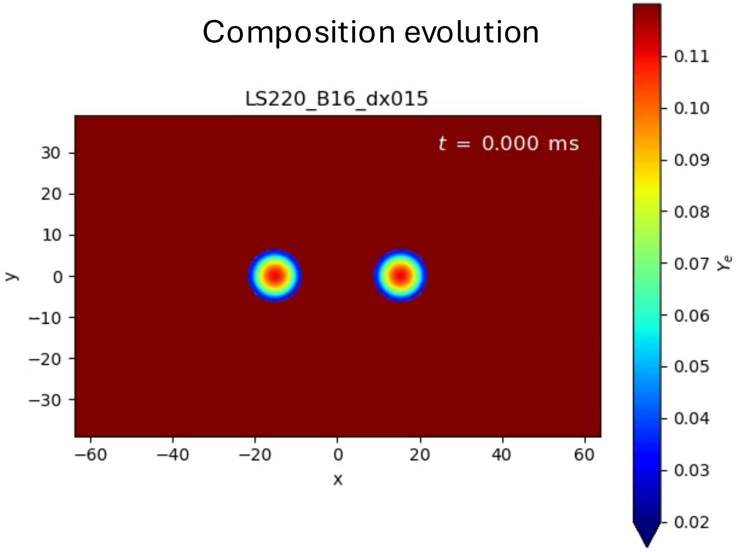


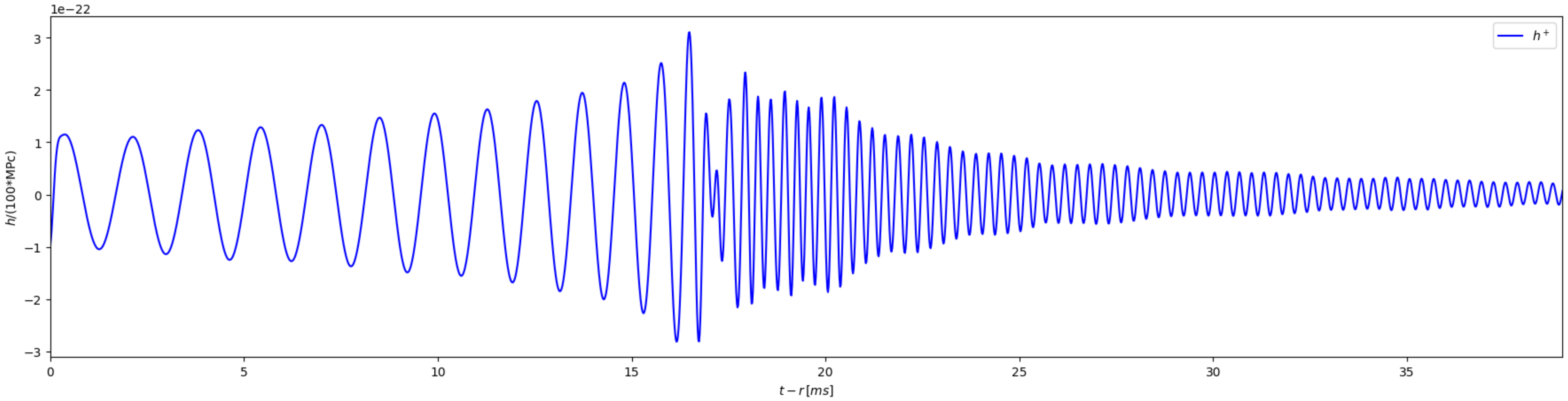
Image credit: Kawamura et al. (2016)

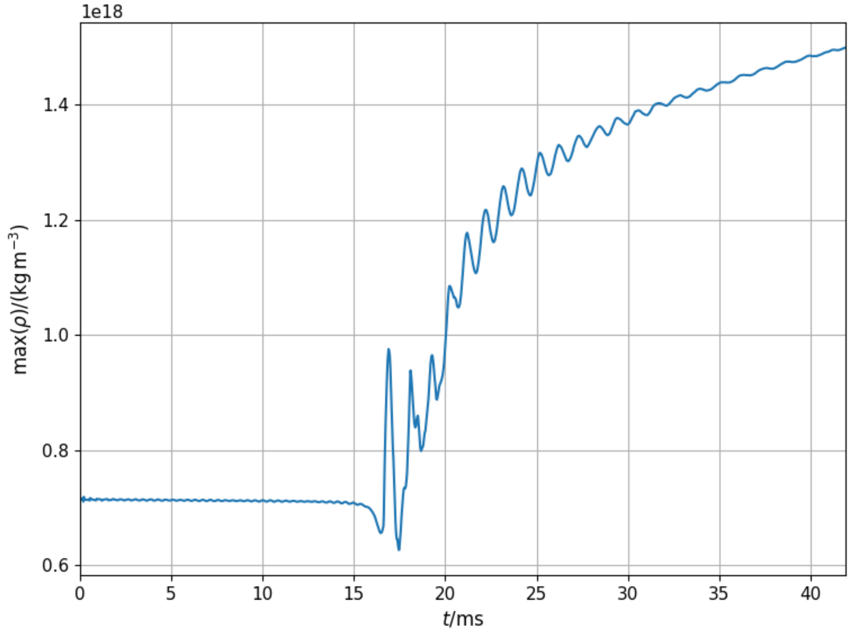
Results: Magnetized-LS220

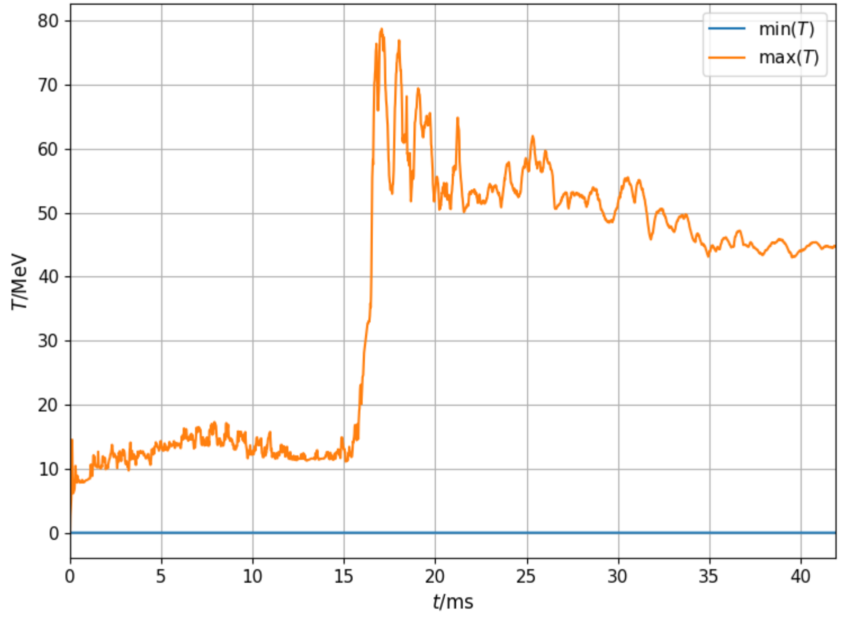






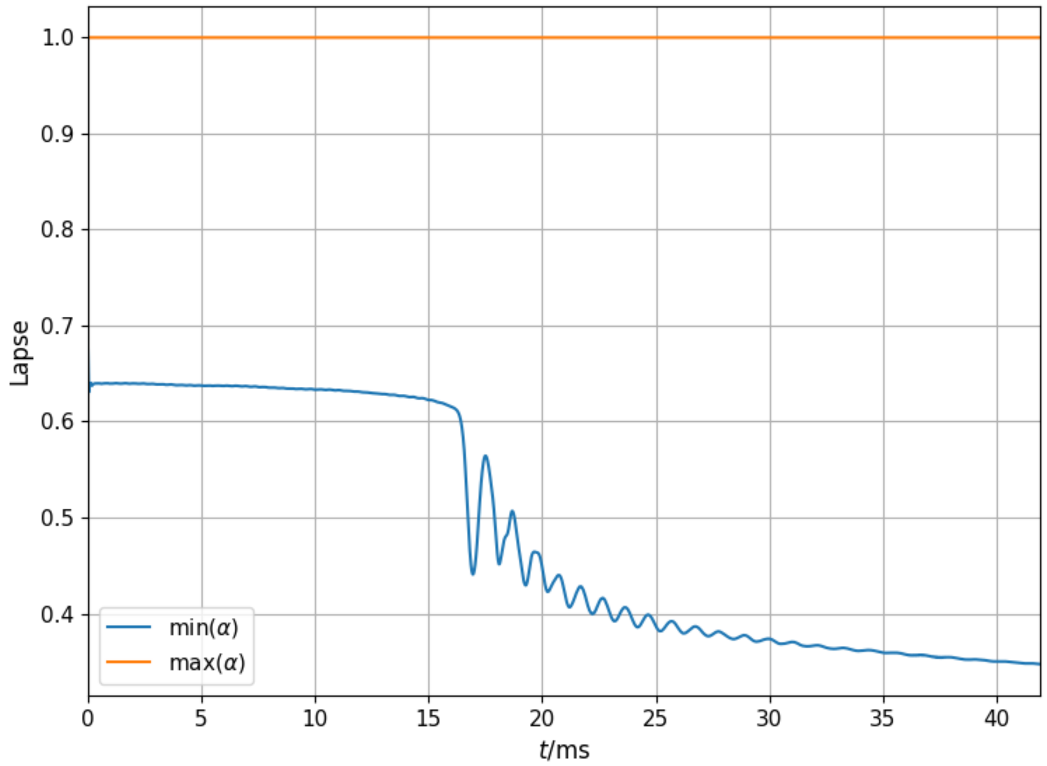




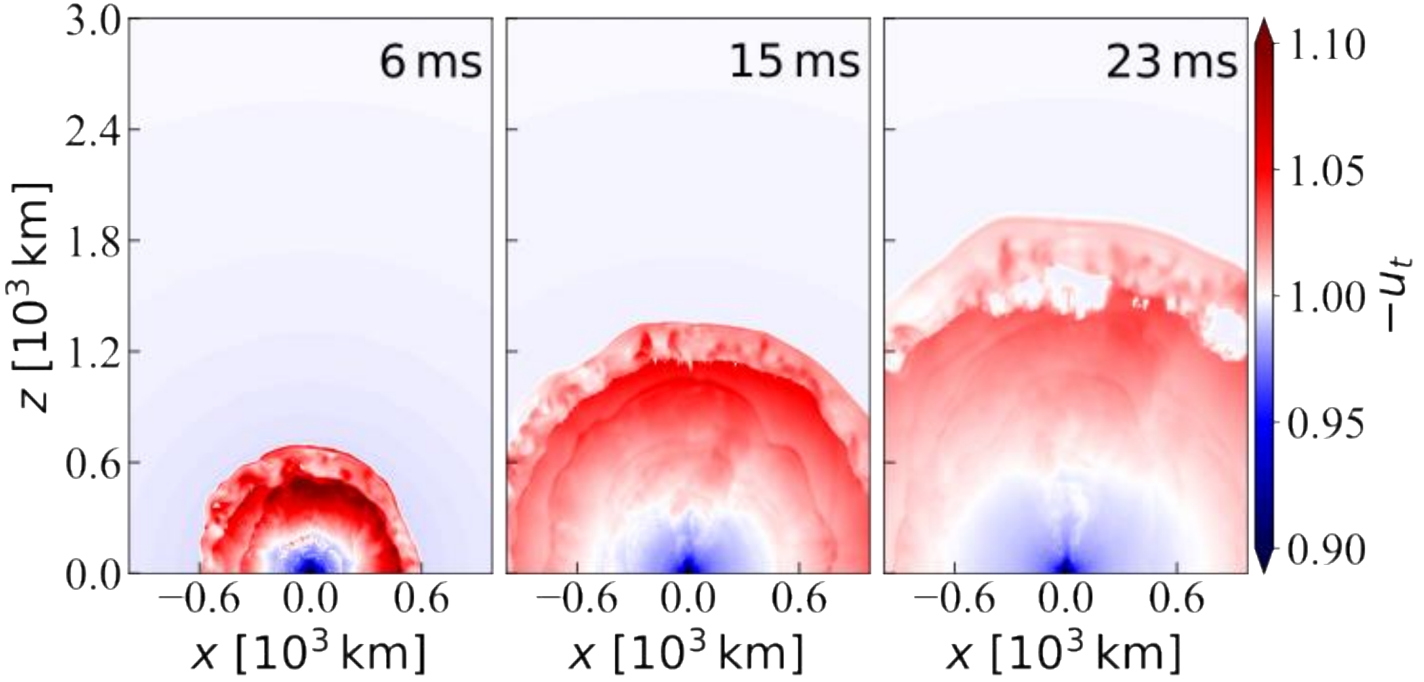


Results: Collapse diagnoses

- Merger happens at t~17 ms
- Late evolution: The maximum temperature is decreasing and the minimum lapse oscillations are damping away.



Results: Outflows

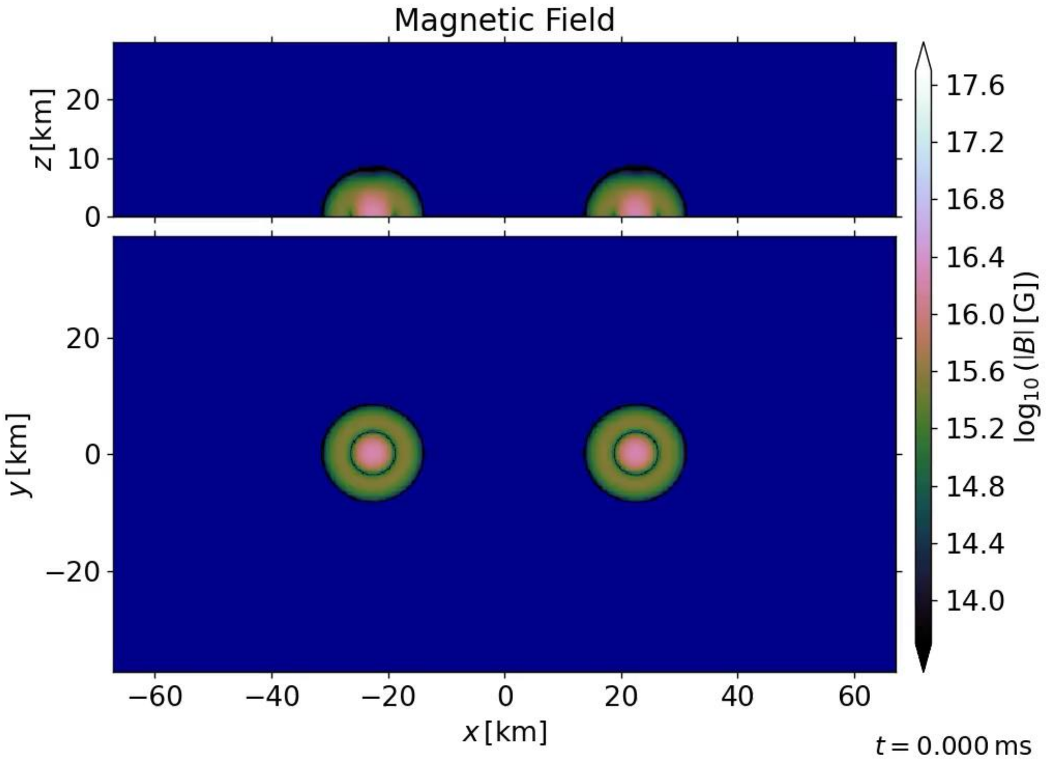


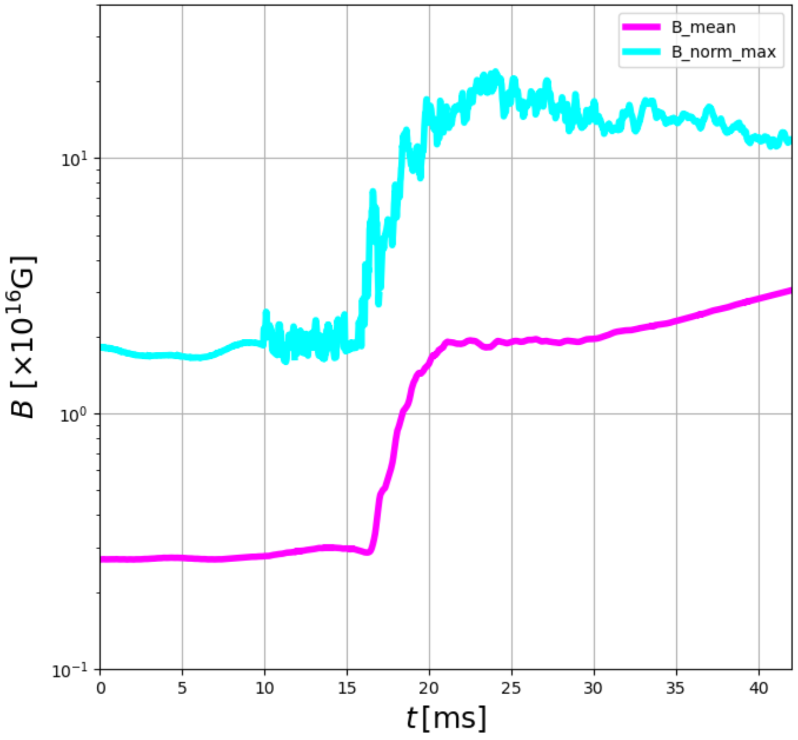
The unbound ejecta ($u_t < -1$) is generated due to:

- Shocks and tidal tail during merger (dynamical ejecta).
- Magnetically-driven turbulence (post-merger)
- Spiral-wave (angular momentum transport caused by M1 instability in the case of long-lived HMNS remnant)

The luminosity and light-curves of the kilonova emissions can be estimated from (M_{ej},v_{ej},$Y_{e\ ej}$).

Results: Magnetic field evolution





Magnetic field is amplified by order of magnitude due to KHI and MRI

Results: MRI analysis

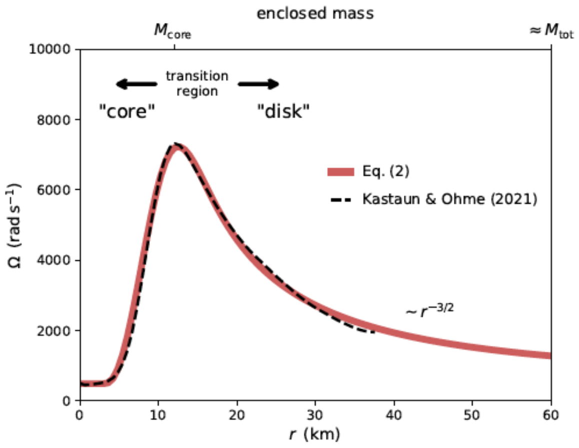
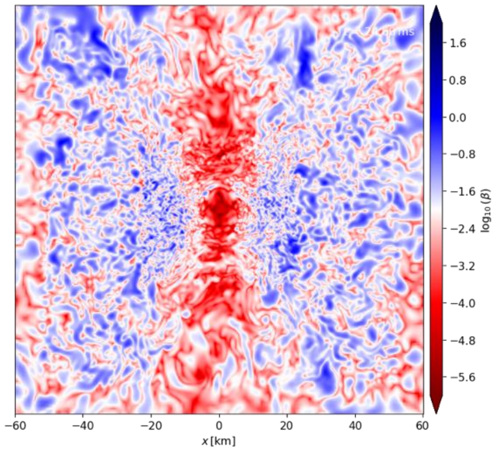
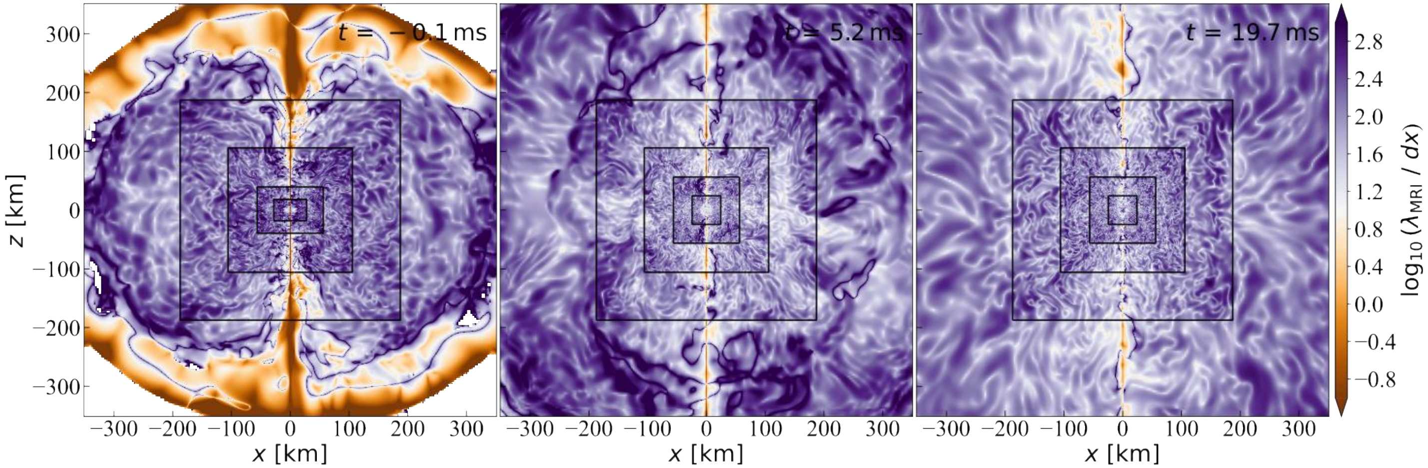


Image credit: Margalit et al. (2022)



β at $t-t_{merger}$ = 24 ms



Number of grid points along the MRI fastest growing mode wavelength at merger time, t~5 ms and t~20 ms after merger.

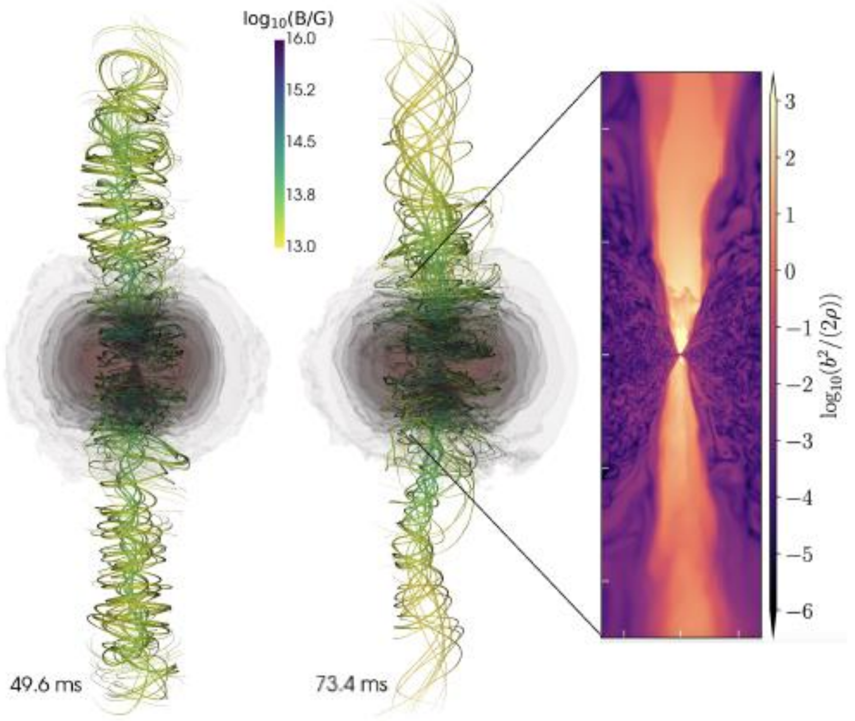
Criteria for MRI:

- Differentially rotating disk/envelope with negative gradient in the rotation profile.
- Magnetic field effects are considered as small perturbation:
  $\beta = P_B/P_{gas} \sim 0.001 - 0.1$
- The wavelength of the fastest growing mode should be resolved at least by ten grid points:

$$\lambda_{\rm MRI} \approx \frac{2\pi}{\Omega}\frac{B}{\sqrt{4\pi\rho}}$$

Current status for Spritz: Low-density treatment

- We usually set $\rho_{atm} \sim 10^{-10}$ of ρ_{max} for numerical purpose
- Large scale simulations: ρ_{atm} is too dense, impacts the incipient jets and ejecta
- Kalinani et al. (2025) made ρ_{atm} decay rapidly $\rho \sim r^{-6}$ for r>74km, computational grid r=51500 km (polytrope EOS)
- For tabulated EOS: smooth transition from nuclear EOS to Helmholtz EOS for $\rho<10^3$ g/cm^3 (Hayashi et al (2022)).



Kalinani et al. (2025)

Summary and Future Work

- **So far…**
- Successful low-resolution, short tests from inspiral, merger to early postmerger phases (delayed collapse of HMNS to BH as expected).
- Production simulations: magnetized and non-magnetized for BLh and LS220 EOS (code comparison for short-lived and long-lived remnant, investigating jet formation)
- Extending EOS table for low density atmosphere treatment $\rho \sim r^{-6}$ (for outflow studies at large scale simulation, *Kalinani et al. (2025)*)
- **For Future…**
- Extending magnetic field outside the neutron star (for robust jet formation)
- Using more advanced neutrino treatment (M1)


GRAZIE